

# Vacuum-ultraviolet spectral-irradiance calibrations: method and applications

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A method to determine the spectral irradiance of a radiation source in the vacuum ultraviolet through the use of recently developed spectral-radiance standards is described. The method has been applied between 138 and 310 nm, and the spectral irradiances of several different light sources have been measured on an absolute scale with estimated uncertainties less than 10%.

The quantitative measurement of the intensity of an unknown radiation source is often done by comparing the output of the source with that of a standard radiation source. To a large extent, such calibrations in the vacuum ultraviolet (VUV) are limited by the scarcity of convenient radiation standards. In recent years, various sources have been developed as standards of spectral radiance in the VUV.<sup>1-4</sup> However, there are still no standard sources of spectral irradiance, except for certain synchrotron radiation facilities, for wavelengths shorter than 200 nm. As a first step toward establishing standard sources of spectral irradiance in the VUV, this Letter describes a method of calibrating the spectral irradiance of an unknown radiation source based on an existing standard source of spectral radiance. The method is applied to several sources that are being applied as irradiance sources in various experimental situations, e.g., on board the Space Shuttle.

Spectral radiance ( $\text{W cm}^{-2} \text{ nm}^{-1} \text{ sr}^{-1}$ ) is the power radiated from a specific emitting surface ( $\text{cm}^2$ ) in a certain wavelength band (nm) within a given solid angle (sr). The spectral irradiance ( $\text{W cm}^{-2} \text{ nm}^{-1}$ ) defines the radiant power incident upon a specific target area ( $\text{cm}^2$ ) in a certain wavelength band (nm). The root of the problem of establishing a spectral-irradiance scale based on a radiance scale is that the radiance is normally calibrated only for a small portion of the light source, usually that portion that can be considered homogeneous. Thus the radiation source must be used in such a way that only radiation from the calibrated area reaches the measurement system. This can be done by the use of optical imaging or by the use of collimating apertures.<sup>5,6</sup> For applications in the VUV, the method using collimating apertures has proven more practical and is the basis for the measurements described here.

The collimating aperture method is as follows. A radiation source that is homogeneous over a certain emitting area and whose spectral radiance has been previously determined is situated a given distance from a monochromator. A pair of apertures, one at the entrance slit of the monochromator (the field aperture) and the other as close to the source as possible (the source aperture), is chosen so that only the radiation from the homogeneous portion of the source is mea-

sured. The spectral irradiance at the field aperture is given by the product of the known spectral radiance of the source and a geometric factor dependent on the aperture dimensions and their locations relative to the lamp. This geometric factor contains the information on the effective area of the emitting source, the solid angle of the radiation beam incident upon the field aperture, and the irradiated area.

In principle, these quantities can be determined by measurement. However, a direct determination of the geometric factor is unnecessary, as is shown by the following discussion. The response of a spectroradiometer as a function of wavelength to a suitably collimated radiance standard is essentially a measure of the system detection efficiency on a relative scale. If the same spectroradiometer is irradiated with an unknown source and the response is measured again, the spectral irradiance of the unknown source can be determined, also on a relative scale. Then, provided that the wavelength range of calibration extends to the visible or near-UV region in which standard sources of irradiance are available, the absolute spectral irradiance of the unknown source can be determined at one wavelength within the calibrated wavelength range. This absolute value can then be used to normalize the relative scale of irradiance to an absolute scale.

The calibration procedure is illustrated in Fig. 1. If  $E_x(\lambda)$  is the spectral irradiance at wavelength  $\lambda$  of the source whose irradiance is to be determined, the response  $S_x(\lambda)$  of the spectroradiometer to this radiation source [see Fig. 1(a)] is

$$S_x(\lambda) = E_x(\lambda)\alpha(\lambda), \quad (1)$$

where  $\alpha(\lambda)$  is the spectroradiometer system efficiency. The response  $S_R(\lambda)$  to the apertured radiance standard [see Fig. 1(b)] is

$$S_R(\lambda) = L_R(\lambda)\alpha(\lambda)\gamma, \quad (2)$$

where  $\gamma$  is the geometric factor discussed above and  $L_R$  is the spectral radiance of the radiance standard. The relative spectral irradiance can then be determined:

$$E_x(\lambda) = \gamma \frac{S_x(\lambda)}{S_R(\lambda)} L_R(\lambda). \quad (3)$$

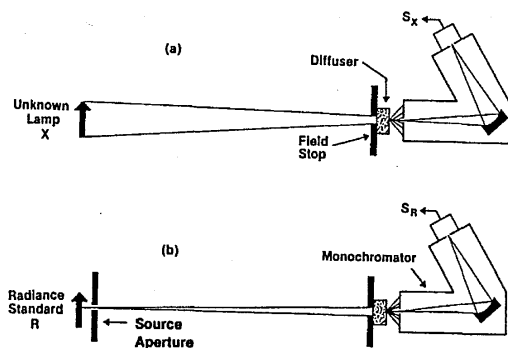


Fig. 1. Schematic of calibration procedure. (a) Spectroradiometer is irradiated by the lamp whose spectral irradiance is to be evaluated, (b) efficiency is determined on a relative scale by irradiation with a stopped-down radiance standards.

The absolute spectral irradiance is determined by comparing the unknown source with an already existing irradiance standard at some convenient wavelength. If it is more suitable, this can be done on a separate spectroradiometer setup, for example, one that is dedicated to spectral-irradiance measurements in the visible. The responses of this system (primed) both to the source to be calibrated,  $S'_x$ , and to the already existing irradiance standard,  $S'_I$ , are measured at one wavelength,  $\lambda_0$ , so that the spectral irradiance of the unknown source,  $E_x(\lambda_0)$ , is given by

$$E_x(\lambda_0) = \frac{S'_x(\lambda_0)}{S'_I(\lambda_0)} E_I(\lambda_0), \quad (4)$$

where  $E_I(\lambda_0)$  is the spectral irradiance of the standard source.

If Eq. (3), with  $\lambda = \lambda_0$ , is combined with Eq. (4),  $\gamma$  can be eliminated to give

$$E_x(\lambda) = \frac{S'_x(\lambda_0) S_R(\lambda_0) E_I(\lambda_0) S_x(\lambda)}{S'_I(\lambda_0) S_x(\lambda_0) L_R(\lambda_0) S_R(\lambda)} L_R(\lambda). \quad (5)$$

From Eq. (5) the absolute irradiance of the unknown source can be determined over the complete wavelength range of the radiance standard.

The considerations given above assume first that the system efficiency of the spectroradiometer employed does not depend on the angle at which radiation enters and second that diffraction effects are not significant. Since several sources with different dimensions are used and since a monochromator grating is used whose reflection efficiency is not expected to be uniform, a diffuser located directly behind the field aperture is necessary to ensure that the first assumption is correct. A  $\text{MgF}_2$  window, ground on one side, was used as the diffusing element. Although it cannot be expected to be as good a diffuser as an integrating sphere, it was shown to be suitable at least over a relatively small range of angles. For the sources described in this Letter, the uncertainty in the spectral irradiance that is due to the nonideal diffusing properties of the diffusing window was measured to be less than 1%.

We must also consider possible effects of diffraction.

In the case of an extended homogeneous radiation source whose dimensions are large compared with the source aperture, it can be shown that Fraunhofer diffraction effects introduce no wavelength dependence and that the geometric factor is wavelength independent. One can appreciate this qualitatively, perhaps, by realizing that some percentage of the radiation from each radiating point does not pass through the field aperture because of diffraction. However, one can always find a complementary point in the domain of the extended homogeneous source that exactly makes up for this loss. As discussed later, by substituting a different-sized aperture we showed that the inhomogeneity of the real sources used was insufficient to cause any measurable effects that were due to diffraction.

The vacuum spectroradiometer, as already indicated schematically in Fig. 1, consisted of a solar-blind photomultiplier and a spectrometer with a 2-mm-diameter field aperture mounted on a  $\text{MgF}_2$  diffusing window located 50 mm in front of the entrance slit. The diffuser was located some distance in front of the entrance slit in order not to overfill the grating and thereby increase the quantity of scattered light (less than 2% of the weakest signal.)

The light source used as a standard of spectral radiance in the near and vacuum ultraviolet was an argon mini-arc<sup>2</sup> previously calibrated with respect to a primary standard, a wall-stabilized hydrogen arc.<sup>1</sup> Both

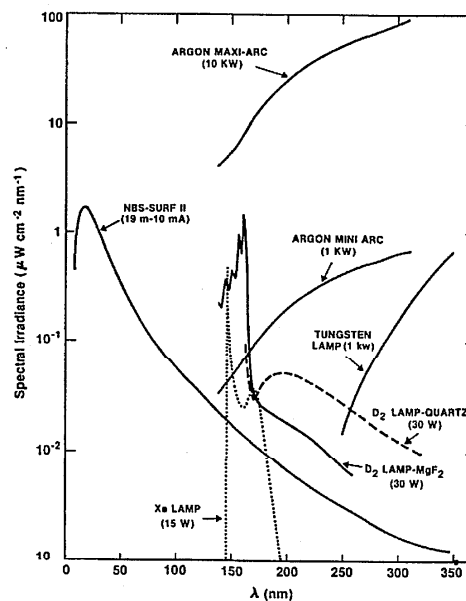


Fig. 2. Absolute spectral irradiance measured as a function of wavelength at a distance of 50 cm from the field aperture for five different continuum sources with the indicated power requirements. The spectrum of the  $\text{D}_2$  lamp with  $\text{MgF}_2$  window below 170 nm, measured for a 1-nm bandpass, is a pseudo-continuum made up of blended lines. Shown for comparison purposes are spectra of the 250-MeV National Bureau of Standards synchrotron radiation facility, for a beam current of 10 mA and a field aperture distance of 19 m, and the tungsten-quartz-halogen lamp, for the standard 50-cm distance.

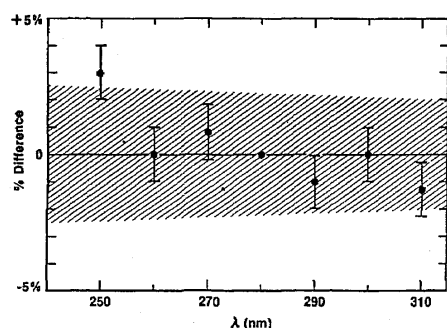


Fig. 3. Percentage difference in the near UV between spectral-irradiance calibrations using conventional techniques (essentially using a tungsten-quartz-halogen irradiance standard and integrating sphere) and the method here introduced for VUV calibrations (essentially using a mini-arc radiance standard and diffusing window). The shaded area represents the uncertainty in the tungsten-lamp calibration. The error bars represent the imprecision in the measurements. The measurements were normalized at 280 nm.

sources have been used before for radiometric purposes and have been subjected to radiometric-scale inter-comparisons, both internal<sup>1,6</sup> and international.<sup>7</sup> The uncertainty in the absolute spectral radiance is estimated to be within 6% between 138 and 330 nm. The mini-arc was located 50 cm from the field stop. A 0.3-mm-diameter aperture placed 5 cm from the mini-arc center was used to restrict the size of the radiating area to about 0.5 mm in diameter.

The light sources calibrated were the following: a 30-W deuterium lamp with quartz window, a 30-W deuterium lamp with  $\text{MgF}_2$  window, an argon mini-arc without collimating aperture, a higher-powered argon arc (the maxi-arc), and a noble-gas dimer lamp. The results, in addition to several reference spectra, are shown in Fig. 2. The total systematic uncertainty in the calibrations, including the uncertainties in the primary source calibrations and the transfer procedure, is estimated to be less than 10%. Although the sources generally emit radiation at shorter wavelengths than shown, the short-wavelength limit is currently set at about 138 nm because of the low signal obtained from the stopped-down mini-arc radiance standard at shorter wavelengths. The broad structure apparent in the  $\text{D}_2$  lamp spectrum below 165 nm is due to blending of Lyman-band molecular lines and is to some extent dependent on spectral resolution. The bandpass for this measurement was about 1 nm. Not shown in the figure are several lines in the argon-arc spectra that are due to residual-gas impurities.<sup>2</sup> The irradiances were put on an absolute scale by measuring the absolute spectral irradiance of the lamps at 280 nm, using a tungsten-quartz-halogen lamp as an irradiance standard. A separate spectroradiometer utilizing a  $\text{BaSO}_4$ -coated integrating sphere, a predispersing monochromator, and an analyzing spectrometer was used for these measurements. As shown previously, one measurement of

this type is sufficient, in combination with the relative measurements performed on the vacuum-irradiance facility, to determine the absolute irradiance at all wavelengths.

As a check on the method, it is possible to carry out tungsten-lamp calibrations at other wavelengths between 250 and 350 nm and thus overdetermine the system of measurements. Figure 3 illustrates the percentage difference between the spectral irradiance of the deuterium lamp based on the tungsten-lamp measurements (on the integrating-sphere-double-dispersion spectroradiometer) and the spectral irradiance based on the argon mini-arc measurements (on the diffusing-window-vacuum-monochromator spectroradiometer). The measurements are in agreement within 3%. However, perhaps because the point at 250 nm is a little high, one can perceive a slight trend toward an increasing difference at the shorter wavelengths, i.e., the radiance-based values seem to go lower than the tungsten-lamp-based values. Such a trend would be expected if diffraction played an important role. In order to check on whether the argon-arc plasma was being sufficiently resolved by the collimating system and whether diffraction effects were indeed being accounted for by virtue of the extended nature of the source, additional measurements were taken with a 1-mm aperture used as the field aperture. These measurements should be more sensitive to possible diffraction effects since a smaller percentage of the diffracted beam from each radiating point passes through the field aperture. The spectral distribution of the signal was exactly the same as it was with the 2-mm-diameter aperture, indicating that the data are not significantly affected by diffraction. The measurements also indicate that the spatial resolution was sufficient to define a relatively homogeneous region about the arc axis and that the radiance values applied to the data were appropriate. Thus, if there is a trend in the data of Fig. 3, diffraction effects do not seem to be the cause of it. Future scale intercomparisons, most likely with synchrotron-based calibration groups, are planned in order to extend our range of comparison and to examine our measurement methods further.

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